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Creation and Validation of Sintered PTFE BRDF Targets & Standards

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Abstract

Sintered polytetrafluoroethylene (PTFE) is an extremely stable, near-perfect Lambertian reflecting diffuser and calibration standard material that has been used by national labs, space, aerospace and commercial sectors for over two decades. New uncertainty targets of 2 % on-orbit absolute validation in the Earth Observing Systems community have challenged the industry to improve is characterization and knowledge of almost every aspect of radiometric performance (space and ground). Assuming "near perfect" reflectance for angular dependent measurements is no longer going to suffice for many program needs. The total hemispherical spectral reflectance provides a good mark of general performance; but, without the angular characterization of bidirectional reflectance distribution function (BRDF) measurements, critical data is missing from many applications and uncertainty budgets. Therefore, traceable BRDF measurement capability is needed to characterize sintered PTFE's angular response and provide a full uncertainty profile to users. This paper presents preliminary comparison measurements of the BRDF of sintered PTFE from several laboratories to better quantify the BRDF of sintered PTFE, assess the BRDF measurement comparability between laboratories, and improve estimates of measurement uncertainties under laboratory conditions.

Keywords

Bi-Directional Reflectance Distribution Function; sintered PTFE BRDF; BRF; lambertian; absolute calibration; reflectance target; reflectance standard; ground truth; vicarious calibration

1. LAMBERTIAN REFLECTANCE

A perfect Lambertian reflection material shows no variation with angle as function of the light incidence or detection angle and can be represented by a simple line at $1/\pi \approxeq 0.3183$. The data sets in the paper can be referenced to this ideal value as shown in the example in Figure 1.

The intent of this project was to look at utility of sintered PTFE as a standard for maintaining, transferring, and comparing reflectance scales between instruments. We will discuss actual data results compared to the ideal Lambertian reflector in the conclusions.

2. BRDF & REFLECTANCE TARGETS AND THE NEED FOR LOWER UNCERTAINTY

Lambertian targets are a critical element of ground truth, vicarious calibration, and ground and airborne reflectance-based scaling for radiometric evaluation of remote sensing data. Calibrated absolute reflectance is required as an underpinning of these targets (see Figure 2). Most of these calibrations are done with an 8/d, 8° incidence, diffuse hemispherical (sphere-based) reflectance measure as referenced to a "Lambertian standard" (sintered PTFE or pressed PTFE). Technically, this is an 8/d reflectance factor due to the ratio to the Lambertian material, but this distinction will not be discussed in this paper. The nice part of the 8/d reflectance factor configuration is it is an extremely low uncertainty and a very robust measurement due to removal of any angular dependence. This removal of angular dependence is not something that can be easily be done in field target measurement. Very often the targets are measured at a very specific incidence and collection angle (typical would be 0° incidence (the sun) and near normal, 30° or 45° collection) making it an *angle–dependent measurement*. The 8/d geometry calibration can be applied with low uncertainty of the geometry if measurement is similar. If the geometry is different, then the BRDF must be known or the above errors in Figure 1 may be incurred. Certainly, if the desired uncertainty in the measurement is less than 2 %, a current requirement for many space programs today, then having quality, quantized absolute BRDF *is required*. As can be seen from Figure 1 actual target BRDF can vary by a few percent from an ideal $1/\pi$ level even on "Lambertian samples". Being able to quantize the exact reflectance for each particular measurement scenario demands a portable, traceable, artifact for BRDF transfer.

3. BRDF HARDWARE DESCRIPTION & VALIDATION

All of the BRDF instruments used in this comparison are different – some are commercial, others are custom-built unique solutions. Each instrument used has different illumination and detector mechanisms. Those source/detector and other instrument differences are the primary reasons why inter-comparison with a common artifact may be necessary for establishing a better overall baseline for the industry.

The instruments used by most of the participants in this study have been described in reference papers and websites cited at the end of this document [5–8]. Labsphere recently acquired a REFLET 180 Goniophotometer [9] as a primary BRDF measurement tool. It is described here.

The principal elements of the optical bench are:

- Illumination module: comprising an optical system with 2 diaphragms and a motorized 1-axis goniometer (rotation angles = θ_ι).

- Detection module: comprising an interchangeable optical bloc and a motorized 2-axis goniometer (rotation angles = θ_d, φ_d).
- Sample holder area (platen).
- Enclosed optical bench (“dark chamber”) for best control of stray light

The illumination module is designed to give the operator full control of the parameters of the illuminating beam:

- Spot size (by adjusting a continuous diaphragm) - the continuous diaphragm allows for spot sizes in the range of 1 mm to 13 mm. 5 mm was the chosen spot size for this discussion.
- Flux (by adjusting an indexed diaphragm) - the flux diaphragm is indexed over 4 positions (∅1 = 0.2 mm, ∅2 = 0.4 mm, ∅3 = 1.4 mm, ∅4 = 2.8 mm). The choice for this discussion is ∅3 = 1.4 mm.
- Incidence angle (by rotation of the θ_ι goniometer).
- Illuminance level on the sample surface varies in the range 100 lux to 25000 lux according to the selected diaphragm positions.
- Spectrum of the source is visible light provided by a dichroic lamp with a 6 position filter wheel.

The detection module gives the operator control over:

- Size of the observed area on the sample surface (by selecting one of the 3 interchangeable optical blocks – 0.04°, 1.10° and 2.00° respectively). The choice for the discussion in this paper is the 1.1° block.
- Scattering angle (by rotation of the goniometer)
- Interchangeable optical block determines the size of the observed area on the sample and the angular acceptance of the collected beam.

4. RESULTS OF VALIDATION OF LABSHERE’S BRDF INSTRUMENT

The instruments used by most of the participants in this study have been well characterized for performance [5–8]. In this section, the characterization process of Labsphere’s BRDF instrument is described.

Labsphere used an un-calibrated mirror to determine instrument alignment repeatability of the instrument to be ±0.2° based on best internal practices. Next Labsphere used a sintered PTFE sample (calibrated for directional-hemispherical reflectance factor, not BRDF) to evaluate instrument repeatability. Because the sintered PTFE sample is not calibrated for BRDF, resulting data is normalized to $1/\pi$ at viewing angle of 30°.

Labsphere used the following procedure to measure the BRDF of their sintered PTFE sample for a variety of incident angles:

1. Place reference standard in sample holder. The reference standard should be placed into the sample panel holder at the center of rotation with the keyed fiducial

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positioned to the keyway in the panel holder. When positioned correctly, the reference standard should not be able to rotate in the sample holder. Set sample holder rotation to 0°.

2. Set light source to 0° (normal), and detector to 30°.

3. Take 5 detector readings at this point and record them. The average reading will be set to ideal BRDF value (1/π) using the BRDF software, and can be used to scale measurements taken after this reference.

4. Scan the detector from $\phi_d = -90°$ to 90°. Using the software, convert detector readings to BRDF plot. Values obtained from the scan must fall within 2σ of typical results with BRDF machine at −45°,−30°,−15°, 15°, 30°, and 45°. Figures 3 and 4 below show the acceptable range for each incidence angle.

From the table below for 0° incidence, the scans (−90° to +90°) of sintered PTFE were shown to have the following norms for a total of (33) readings taken over 10 months (normalized at 30° viewing angle).

As near normal incidence is only one condition for illumination, norms for a variety of light source incidence angles were also measured and presented in Table 2 below:

The values recorded for the instrument repeatability and variation with incident angle suggest that the Labsphere instrument can measure BRDF within a 2 % tolerance for shallow angles (< 45°).

5. CREATION OF BRDF TARGET AS AN EXTERNAL VALIDATION ARTICLE

With an instrument of known performance, the essential features in a BRDF standard are:

- Known flatness (planarity) of the reflector face versus mounting surfaces with fiducial references.
- A “keyed” feature or fiducial mark to provide orientation awareness and alignment.
- A well dimensioned part with ways to hold the sample securely in place during measurement.
- A protective cover with O-Ring that does not touch the optical surfaces during storage.

Labsphere provided Spectralon samples [9], which met the criteria above, for use in the study. The dimensions of the reflector surface are 50.8 mm by 50.8 mm (2 inch by 2 inch). We initiated a series of baseline BRDF measurements to try to determine an opinion about if such a physical artifact would be a suitable transfer standard between BRDF instruments.

6. DEFINING THE ROUND OF TESTING WITH NATIONAL LABORATORIES AND INDUSTRY

The test procedure was designed to be simple and robust and to minimize the set-up confusion. The agreed test conditions were as follows:

- 10° incidence, broadband source, +/−80° in plane, every 10°
- 30° incidence, broadband source, +/−80° in plane, every 10°
- 45° incidence, broadband source, +/−80° in plane, every 10°
- 10° incidence, green filter source (532nm), +/−80° in plane, every 10°
- 30° incidence, green filter source (532nm), +/−80° in plane, every 10°
- 45° incidence, green filter source (532nm), +/−80° in plane, every 10°
- 10° incidence, red filter source (636nm), +/−80° in plane, every 10°
- 30° incidence, red filter source (636nm), +/−80° in plane, every 10°
- 45° incidence, red filter source (636nm), +/−80° in plane, every 10°

Angles of incidence were chosen to reflect common measurement practices in industry and the aerospace community when using reflectance targets for lab or field use. The value 10° emulates near normal incidence which is common to several international standards and can be well correlated to a near-normal versus diffuse reflectance measurement commonly performed in industry. The values 30° and 45° were chosen as common incidence (and observation) angles because of their common use in ground truth and other technical reflectance measurements (displays, materials, etc.). The extent of +/−80° represents what most BRDF instruments can do with a good signal to noise, higher than 80° was deemed to introduce too much variance. Finally, the measurements were chosen to be in the plane of the incidence angle as out-of-plane measurements add yet another factor (dimension) which might skew the inter-instrument comparison.

The primary objectives of this comparison were as follows:

- Provide a comparison of dissimilar instruments on common artifacts to see if any differences could be discovered.
- Determine viability of the chosen form factor as a test item.
- Qualify a range of differences (if any) and that BRDF indeed is a critical factor in radiometric calibration.
- Establish a foundation for scaling up additional testing with more participants.
- Quantify (if possible) nominal parameters for sintered PTFE on an absolute scale.
- Determine if any spectrally dependent differences occur.

7. RESULTS OF TESTING

Labsphere prepared 8 total samples, measured them, and sent 2 samples each to the 4 participants in the study. Since this is an exploratory effort, conditions of participation were that data could be used anonymously until conclusions were drawn from the performed testing. There is wisdom in this caution as the 5 different instruments, while making the same measurement, are very different structurally and even optically. So at one level, this is as much of an individual system performance question as well as an inter-comparison. The differences are stark: different illumination spot sizes, sources (monochromatic, filtered, broadband), different optical path lengths, collimation tolerances, angular resolutions, and occlusions on the optical path all factor into the results. In fact, one participant was unable to submit results for the comparison because the spot size was too large for the target due to elliptical (cosine) extension of the beam at higher angles.

The unadjusted data is plotted for 3 different incidence angles at 532 nm in Figure 5 and at 636 nm (also 633 nm was used in some cases) in Figure 6. The scale of these graphs should be considered before making a value judgement – if a full scale (0 to 0.40) were used then the fine discrimination in the data would be lost as the measurements – in all cases – showed the material to be quite Lambertian as expected. The following observations were made based on the results:

- <u>Size of Samples/Size of Beam:</u> One key willing participant was unable to provide measurement results because their spot size was too large for the samples due to elliptical (cosine) extension of the beam and higher angles. Larger samples should be used for the next study – a 127 mm (5 inch) square target seems to meet everyone’s criteria without being too large to handle or fixture. This will open our effort to more of the community.
- <u>Orientation of samples:</u> We had specified the orientation of the sample for measurement; however, we did not consider that different instruments have different directions of travel (clockwise versus counter-clockwise). The data presented here has been “flipped” in the figures so we have a common directional travel – this could be a source of error and should be corrected going forward.
- <u>Normalization to 1/π vs. Absolute Scale:</u> Two of the participants provided absolute data (one with uncertainty), and these data sets agreed with each other extremely well. In the other cases, one set of samples was normalized to 1/π at a viewing angle of 30° in the absence of a BRDF reference sample and one data set was set to a higher point (see offset comment below). As the data was delivered only shortly before the paper, we did not have a chance to get back to each participant to discuss this issue. Setting a common scale as an agreed marker should be part of the next effort.
- <u>Systemic Offsets:</u> There appears to be a systemic offset for data provided by one of the participants (samples #7 and #8) resulting in higher values by about 4 %. But, when this offset is removed, the data show excellent correlation with the other participants’ data for all 3 incident angles.

- Alignments: In another case, the angle-resolved shape of the data for samples 1, 2, 5, 6, 7, and 8 at 30° and 45° incident angle suggests a slight misalignment or mechanical issue with the instrument. While both probably have relatively simple solutions, neither issue was addressed in time to correct them for this paper.

- Occlusions: It is normal for most instruments to occlude the incident angle with the source assembly during the collection, but in one data set (#7 and #8) there were two occlusion points. This is not a data issue but only an artifact to report and understand about the instrument configuration.

- Timing: Due to participant schedule, temperamental instrument performance, and high load on these valuable BRDF systems we need to allow at least 6 months (instead of 4) to get full user participation and comments/review on the data.

- Minimal wavelength dependence: One of the participants performed the BRDF measurements (samples 1 and 2) using both filtered and unfiltered (broadband) sources. Comparison of the results shows consistency of values within 1.0 % (and the instrument tolerance) regardless of incidence angle. These results are presented in Figure 7.

The data did reveal some very positive aspects of this type of comparison as well:

- BRDF values from two participants (Samples #1, #2, #5, and #6) agreed very well for all incident angles and both wavelengths. The percent difference between the samples is shown in Figure 11 for the results at 532 nm.

- Data sets for Samples #1, #2, #5 and #6 agreed extremely well. Given that the samples are different and the instruments are also different, one might consider using these values as reference values by which the values produced by the other laboratories could be “corrected.” For such a case, Figure 9 shows the results in which the values for samples #7 and #8 were corrected by removing the systematic offset. Figure 9 shows promise that if we can remove some of the known discrepancies, then we can use these standards as comparison artifacts.

8. CONCLUSIONS

This project was to establish the utility of sintered PTFE as a standard for maintaining, transferring, and comparing reflectance scales between instruments. More work and preparation of the measurement conditions are necessary to truly succeed with a comparison of BRDF measurements. The follow-on work for additional studies to be repeated and expanded are discussed in results in Section 7. In general, agreement between the participants was good. Two of the participants produced values in excellent agreement despite different samples and instruments. The values of the other two participants could easily be “corrected” or “referenced” to these previous values. Also, measurements show that there is minimal dependence of the BRDF values on the source, whether it is spectral (for the wavelengths investigated) or broadband. Together, these results suggest that sintered

PTFE may be a suitable material for transferring BRDF reflectance scales between instruments.

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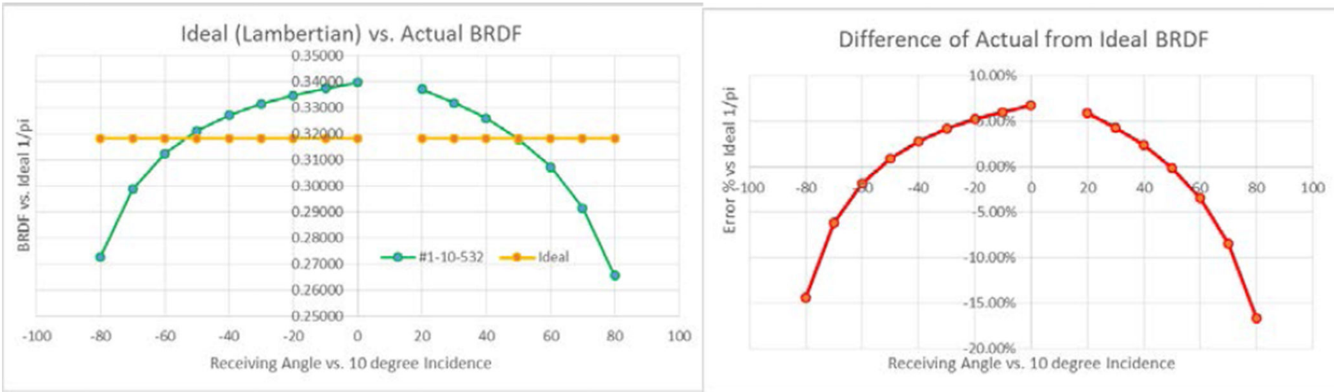

Figure 1.

Ideal Lamberitan BRDF vs. Actual (example) and Delta % from Ideal

Figure 2.
Field Target Measurements

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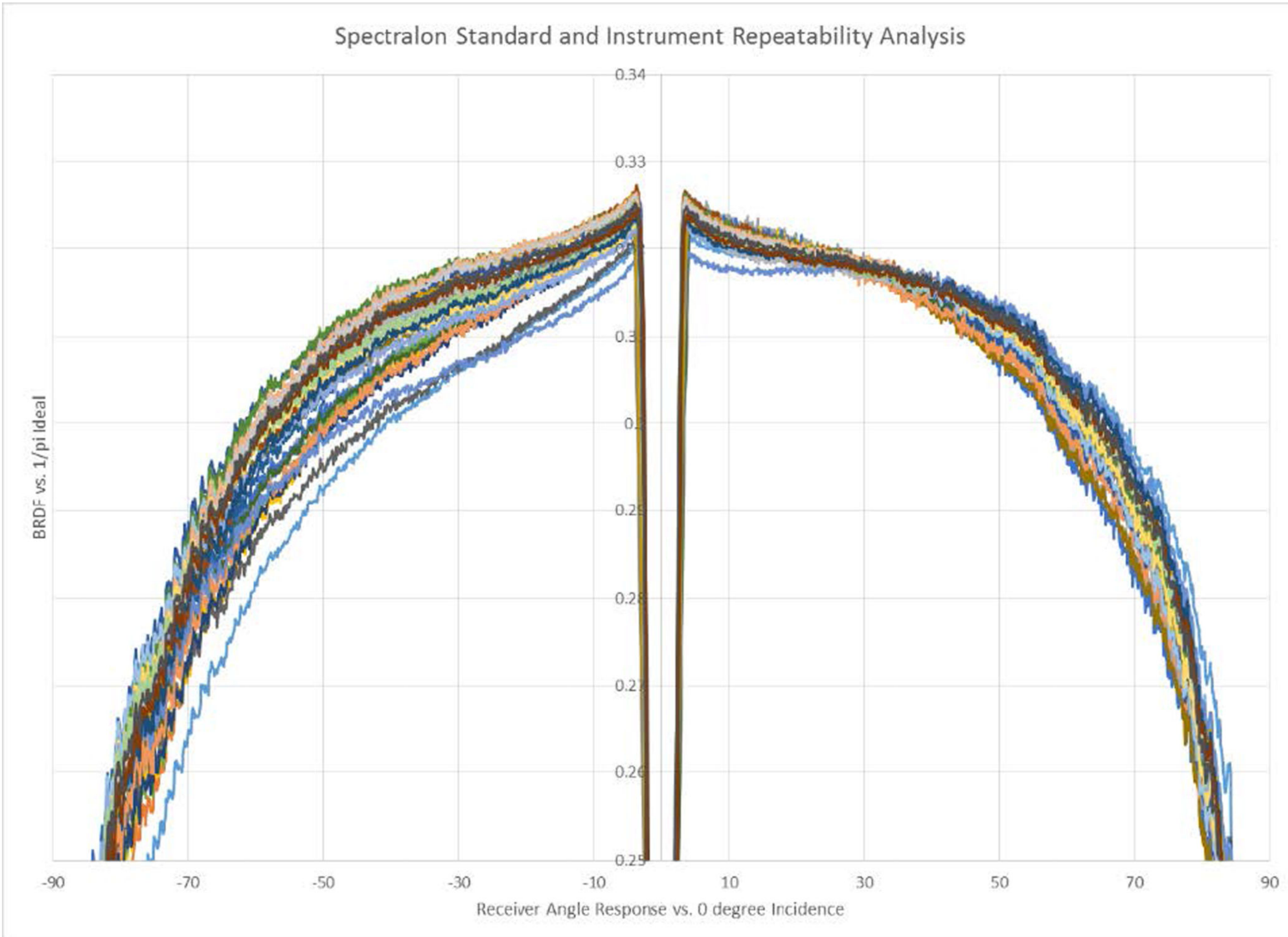

Figure 3.
Repeated measurements of sintered PTFE on Labsphere's instrument

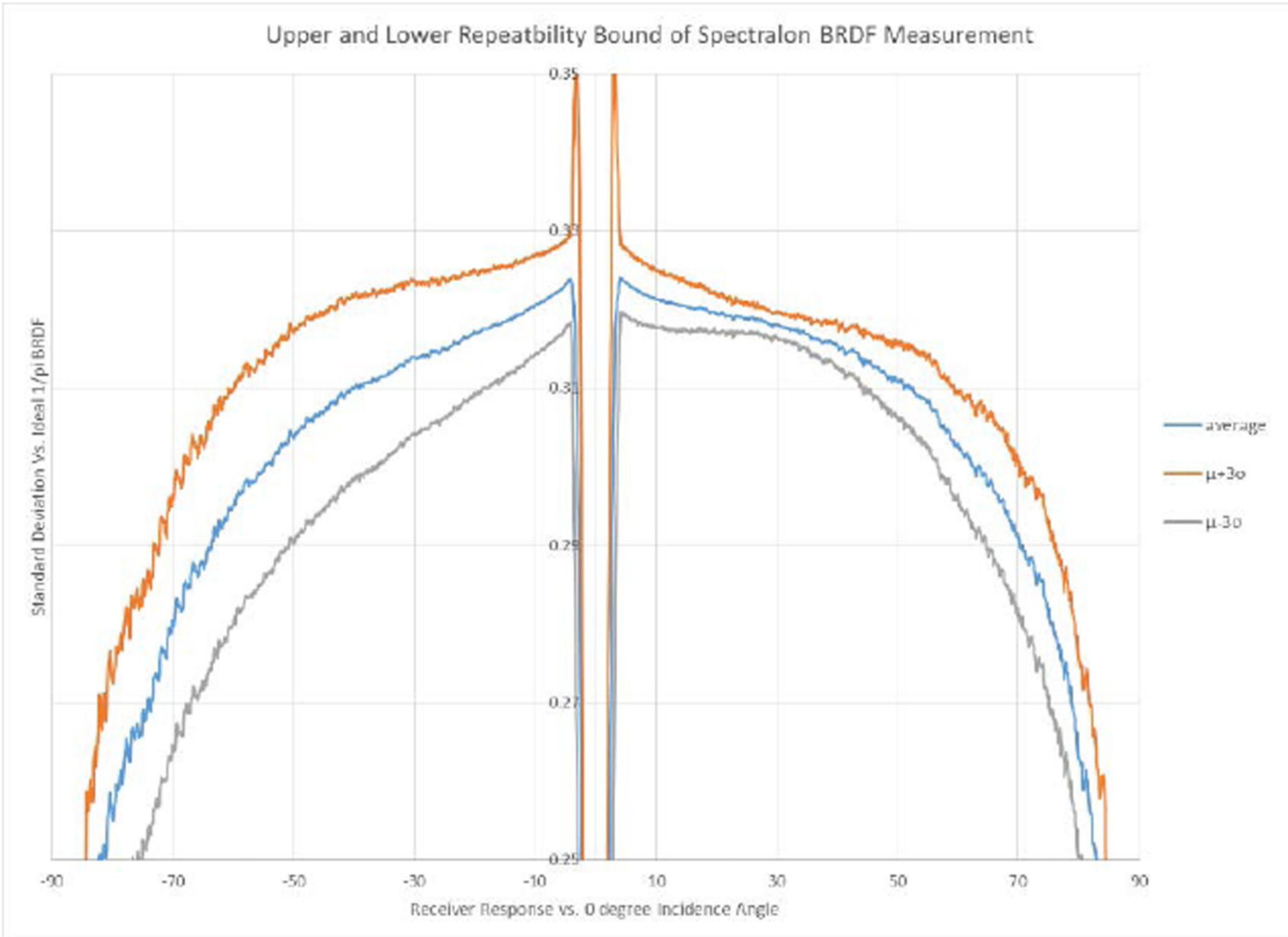

Figure 4.

Tolerance Parameters for sintered PTFE Sample Standard Set from Table 1

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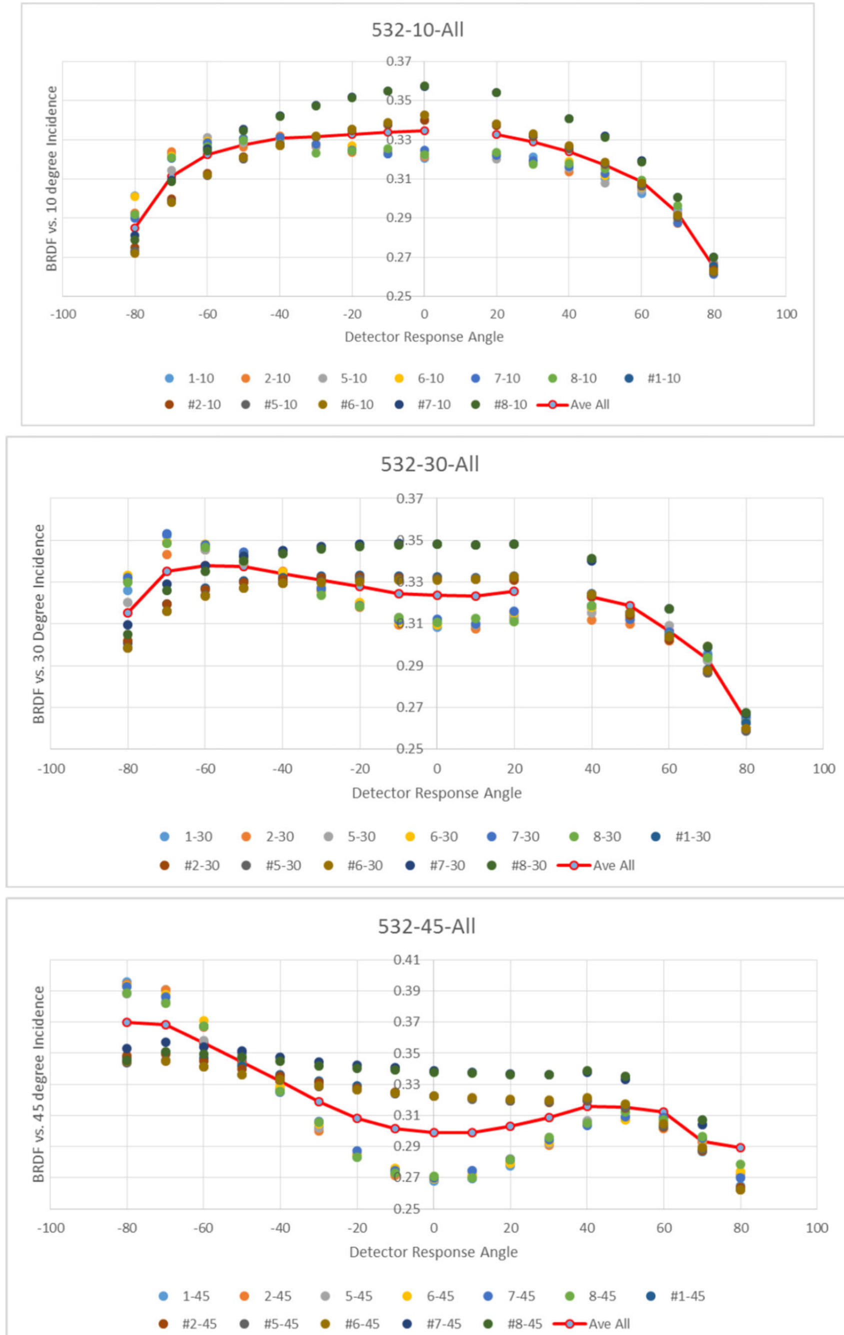

Figure 5.

All BRDF scans on samples at 532nm at 10°, 30°, and 45° incidence.

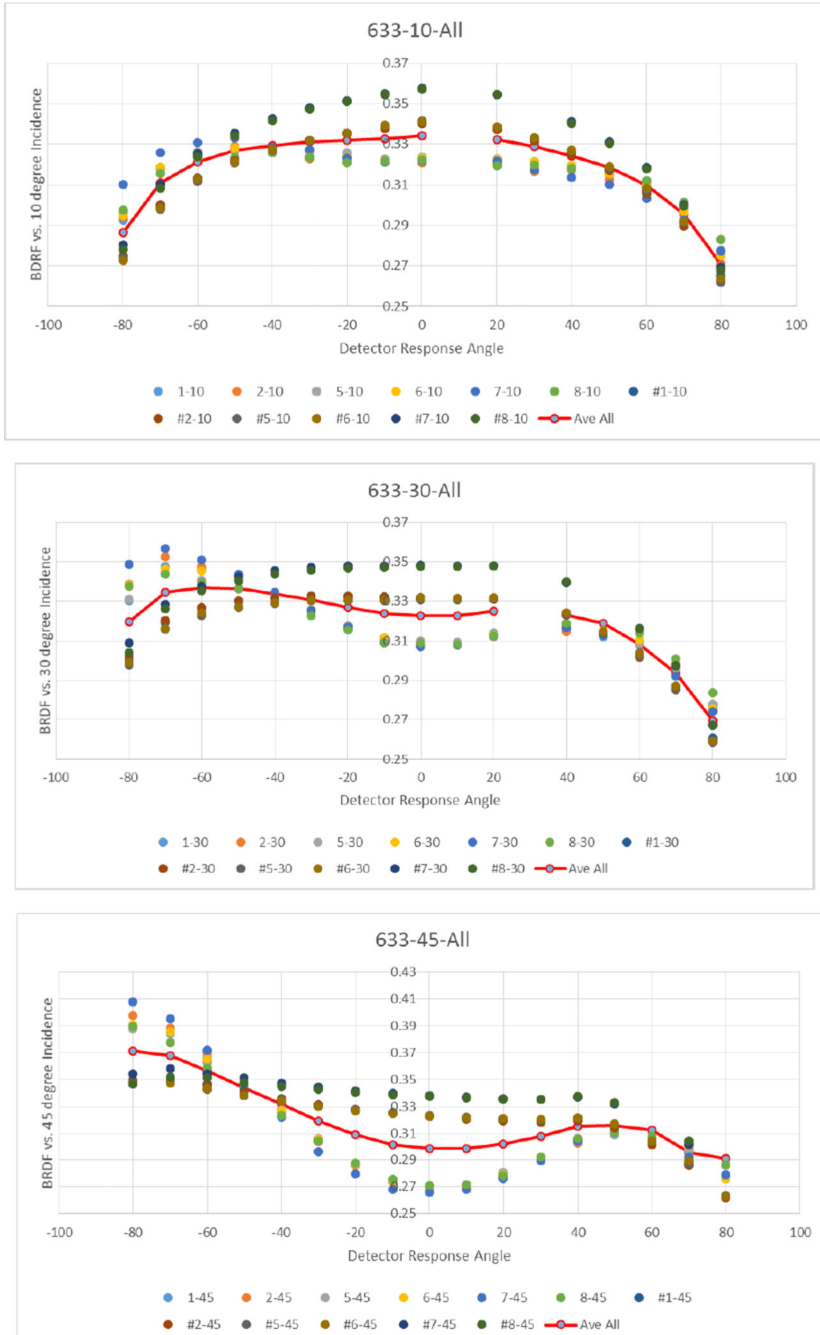

Figure 6.
All BRDF Scans on Samples at 636 nm or 633 nm at 10°, 30°, and 45° Incidence.

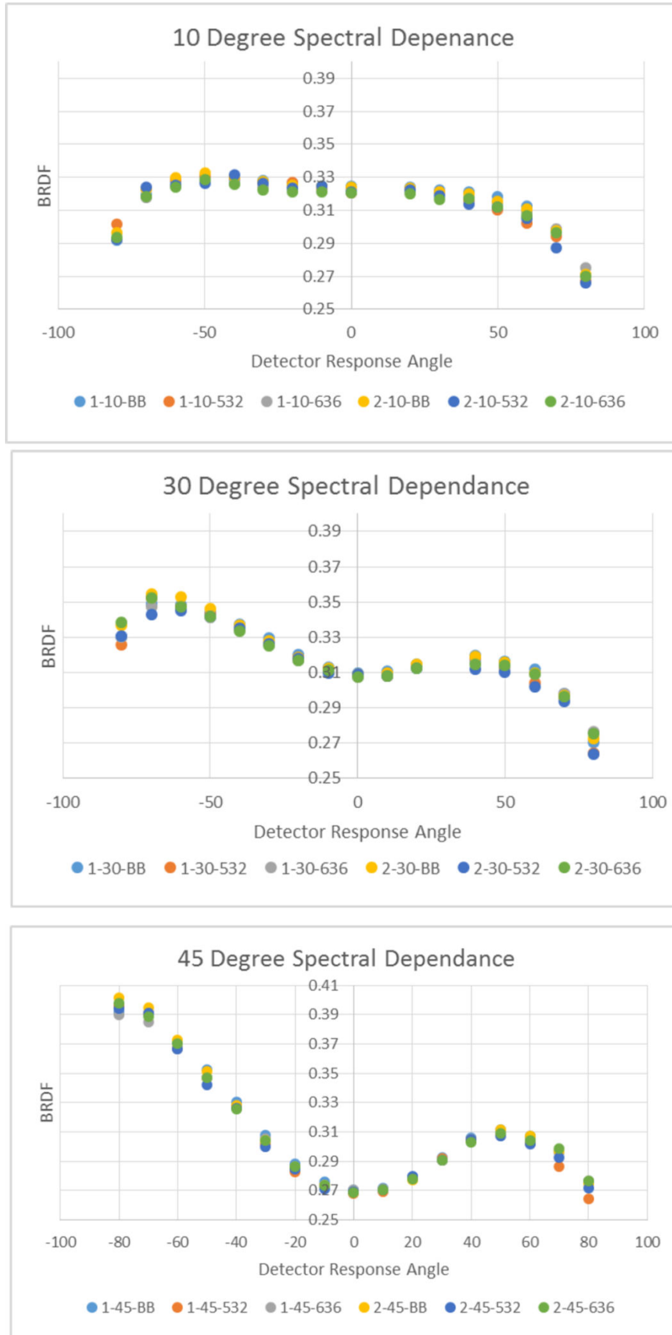

Figure 7.
BRDF Scans on Samples 1 and 2 with Broadband and Filtered (532 nm and 636 nm) Sources at 10°, 30°, and 45° Incident Angles.

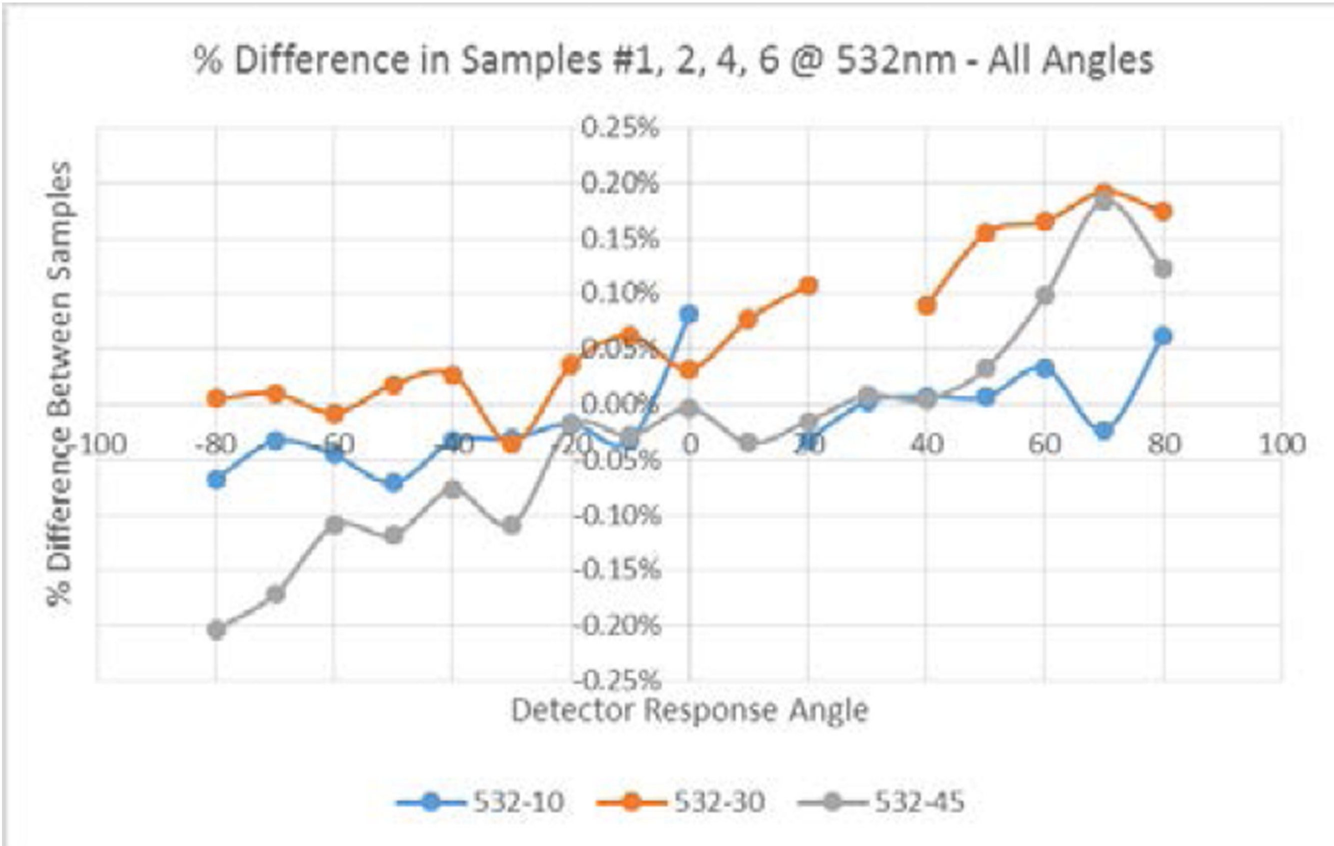

Figure 8.

Agreement of Samples #1, #2, #5, and #6 as shown by percent difference. Similar results for 636 nm not shown

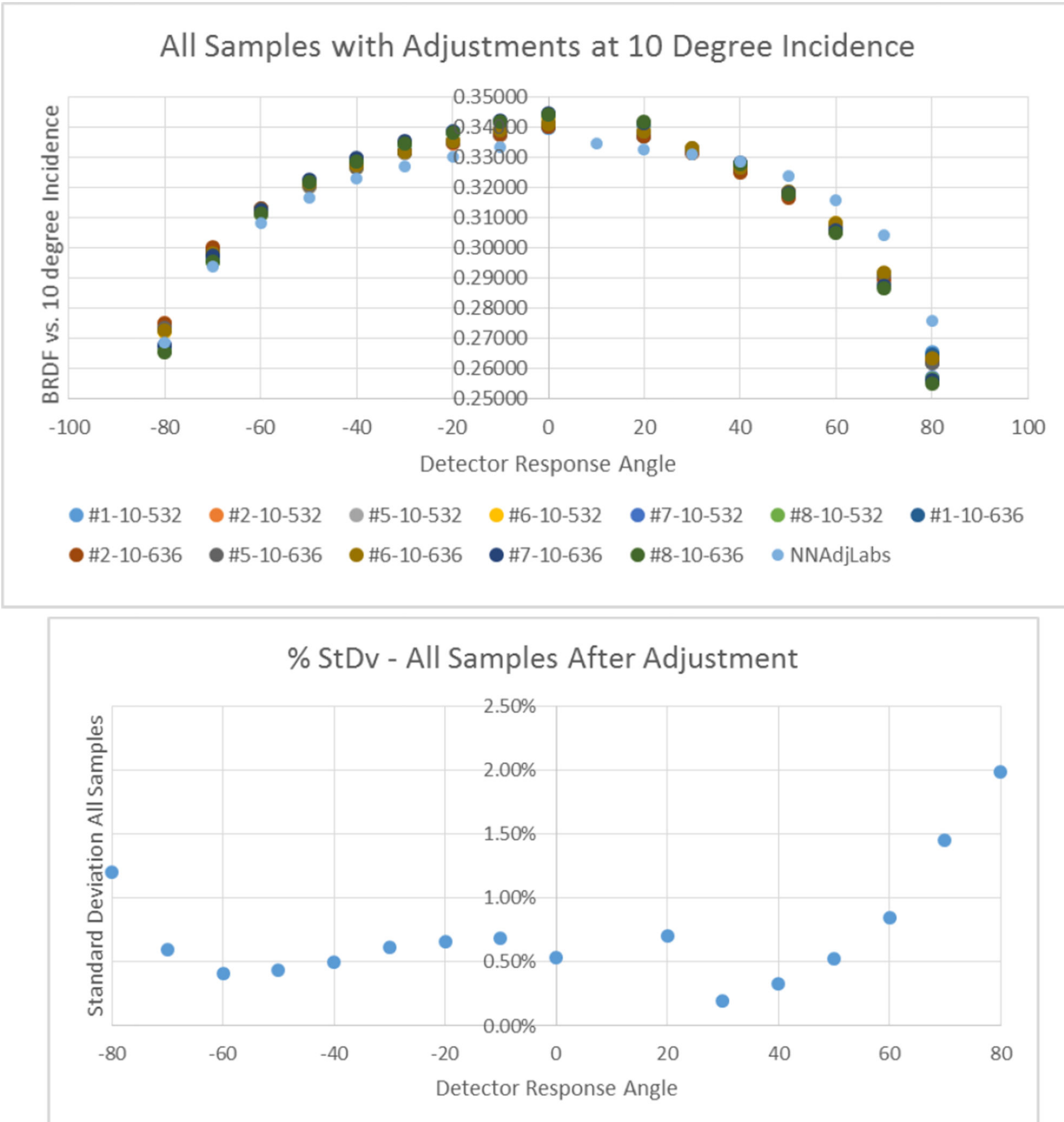

Figure 9.
Re-Normalized to Samples 1, 2, 5, 6: Labsphere and #7, #8 normalization at 10° Incidence and Standard Deviation of All Normalized Samples.

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Table 1

Sintered PTFE BRDF Reference Tolerances

ZERO Degree Incidence			**Lambertian=**		**0.3183**
Theta Lighting	**AVG**	**% Vs. Ideal**	**STDEV**	**μ+3σ**	**μ−3σ**
−80	0.255547	−19.71%	0.00589	0.273218	0.237877
−60	0.295077	−7.30%	0.004958	0.30995	0.280204
−45	0.306734	−3.63%	0.004155	0.319199	0.294269
−30	0.31382	−1.41%	0.003197	0.32341	0.30423
−20	0.317161	−0.36%	0.002565	0.324855	0.309467
−15	0.318368	0.02%	0.002315	0.325312	0.311423
−10	0.320452	0.68%	0.002101	0.326754	0.314151
−5	0.323126	1.52%	0.001921	0.328888	0.317364
5	0.32343	1.61%	0.00137	0.32754	0.319321
10	0.321322	0.95%	0.001243	0.325051	0.317592
15	0.320377	0.65%	0.00106	0.323556	0.317197
20	0.319509	0.38%	0.00085	0.322059	0.31696
30	**0.317963**	**−0.11%**	**0.000535**	**0.319569**	**0.316357**
45	0.313138	−1.62%	0.001271	0.31695	0.309327
60	0.302519	−4.96%	0.002288	0.309383	0.295654
80	0.262821	−17.43%	0.004218	0.275474	0.250169

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Table 2

Sintered PTFE Sample Variation for Different Incidence Angles

Angle (degrees)	μ+2σ	μ−2σ	range	%μ+2σ	%μ+2σ			
−45	0.315	0.2987	0.0163	−1.04%	−6.16%			
−30	0.3202	0.3076	0.0126	0.60%	−3.36%			
−15	0.323	0.3139	0.0091	1.48%	−1.38%	Lambertian Value		
15	0.3224	0.3183	0.0041	1.29%	0.00%	0.3183		
30	0.319	0.3169	0.0021	0.22%	−0.44%			
45	0.3158	0.3107	0.0051	−0.79%	−2.39%			